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SUMMER ABUNDANCE AND ECOLOGY OF ZOOPLANKTON IN THE GULF STREAM

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The Gulf Stream is an important ocean current that has been studied intermittently hydrologically and biologically. The hydrology includes the causes and theories of the Gulf Stream flow and meanders, all of which have been well summarized by Stommel (1958). Biological transects across the northern portion of the Gulf Stream (south of the Grand Banks) have been made by Clarke (1940) and Grice and Hart (1962), with the objective zooplankton description on either side as well as in the Gulf Stream.

However, it is of interest to trace continuously the zooplankton population density in a volume of water as it drifts north in the Gulf Stream flow for a considerable portion, attempt to correlate it with the hydrology, and hopefully arrive at some ecological relationships. These relationships would include the incident solar radiation, primary production, grazing by zooplankton, effects of surface winds and Gulf Stream eddy viscosity on mixing and water transport, and effect of dissolved minerals on zooplankton population. This is indeed a formidable objective and would require a very extensive observational program to accomplish completely; fortunately, we were able to acquire data for this analysis in July–August 1969 from the USNS Lynch (T-AGOR 7) and a manned submersible, the Ben Franklin (PX-15). The drift of the Ben Franklin was closely followed with the locations of 42 horizontal tow samples taken from the Lynch (Egan, 1974).

The three zones of water between our eastern coast of the United States and Bermuda are of great biological interest because of their extreme contrast (Clarke, 1940), in particular the Gulf Stream and the slope water, which is the area of mixing of the continental slope water with the Gulf Stream. The Sargasso Sea bounds the eastern and southern boundaries of the Gulf Stream. Clarke's (1940) sampling program consisted of oblique hauls (one shallow and one deep) at nine stations along a transect south of the Grand Banks. Grice and Hart (1962) also made oblique tows in the same general area.

However, our hauls were horizontal at various depths because we sought to determine whether there was a variation in zooplankton populations with depth and location in the Gulf Stream. A single oblique tow throughout the water column at each station would have yielded far more reliable data on zooplankton abundance and biomass, but no information on the depth distribution. The depth distribution of zooplankton in the Gulf Stream is an important parameter, and the sampling program was planned to follow the course of the free drift of the Ben Franklin

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in the Gulf Stream. Thus the same region of the Gulf Stream would be sampled as it flowed north. During the free drift north of the Ben Franklin, optical measurements of the chlorophyll-*a* and chlorophyll degradation products were also made as a function of depth (Egan, 1974). It would then be possible to seek a relationship between these determinations and the depth distribution of zooplankton. Because of the low zooplankton population density, long duration tows were required. Also, for measurements of phytoplankton population, as indicated by the amount of chlorophyll-*a*, a very sensitive fluorescence measurement technique was required because of the low level of chlorophyll-*a* i.e., less than 1 $\mu g/l$ in the open ocean (Yentsch and Menzel, 1963).

The hydrology of the Gulf Stream becomes important when we consider the greatly increased volume of water transport as the Gulf Stream expands from Cape Kennedy northward. This requires mixing with adjacent slope waters, concomitant with surface mixing caused by winds and tides. The transport at 30°30′N (off Jacksonville, Florida) is 37.2×10^6 cubic meters/second and at 32°30′ N (off Charleston, South Carolina), it is 53.0×10^6 cubic meters/second (Richardson, Schmitz, and Niiler, 1969). Further, a compilation of data by Knauss (1969) indicates the transport at 34°45′ N (off Cape Hatteras, North Carolina) to be 60×10^6 cubic meters/second (Barrett, 1965), and at 37°35′ N 65° E (south of Nova Scotia) to be 147×10^6 cubic meters/second (Fuglister, 1963). Coastal oceanographic and sedimentologic interpretation of Apollo IX space photographs show plume like patterns of sediment bounding the western edge of the Gulf Stream (Mairs, 1970). It would be assumed that some of these sediments with some of the biota in these coastal waters enter the Gulf Stream. Further, the lateral meanders and detached eddies of the Gulf Stream between Cape Hatteras and the Grand Banks (Hansen, 1970) would also cause mixing with adjacent waters, together with momentum transfer with the resulting observed water-transport increase (Knauss, 1969).

Tides would not be expected to cause any appreciable mixing effect, but would cause divergences: *i.e.,* a westward tide in the cooler Sargasso Sea would result in this water flowing down and under the Gulf Stream. Mixing with the Gulf Stream could occur by eddy turbulence along the edge irregularities (von Arx, Bumpus, and Richardson, 1955), caused by turbulent shearing stresses, as yet poorly elucidated (Stommel, 1958).

Minerals picked up by the Florida Current in the Gulf of Mexico and Caribbean Sea (Jacobs and Ewing, 1969) are transported into the Gulf Stream, possibly providing nutrients for primary production.

Primary production in the Gulf Stream is nutrient- or micronutrient-limited, since there is low attenuation by the sea water of incident solar irradiance. The amount of primary production in the Gulf Stream may be inferred from a measurement of chlorophyll-*a* and chlorophyll degradation products. This primary production in turn will support the Gulf Stream zooplankton populations. An ecological analysis could utilize previously published Gulf Stream measurements of cholorophyll-*a,* chlorophyll degradation products, and dissolved minerals.

TABLE I

Haul data and results.

Haul Stations	Latitude, °N		Longitude, °W		Depth of Tow, m	Duration of Tow (min)	Time Begin Tow (Z)	Surface Temperature °C	Date (1969)	Major Taxa Present	Ratio of Zooplankton to Phytoplankton
	Begin	End	Begin	End							
1	29°06.2′	29°08′	79°51.2′	79°51.1′	250	34	2242	30.1	18/7	16	3.0
2	29°32.2′	29°34′	79°50.1′	79°51′	306	30	1428	30.1	19/7	17	1.0
3	"	"	"	"	322	30	1428	30.1	19/7	14	0.97
4	29°50.3′	29°52.5′	80°00.6′	80°00.5′	310	60	2217	29.9	19/7	18	5.1
5	30°15.9′	30°18′	79°56.8′	79°58.0′	89	30	1530	29.9	20/7	16	8.0
6	30°36′	30°40′	80°03.6′	80°06.0′	25.7	60	2319	29.3	20/7	16	3.5
7	"	"	"	"	141	60	2319	29.3	20/7	20	10.7
8	31°22.0′	31°25.8′	79°35.0′	79°35.6′	22.6	60	2000	29.6	21/7	10	1.2
9	"	"	"	"	224	60	2000	29.6	21/7	20	2.3
10	"	"	"	"	1	60	2000	29.6	21/7	17	0.13
11	31°14.4′	31°16.6′	79°04.0′	79°03.0′	25.8	57	0051	29.4	22/7	19	2.1
12	31°19.5′	31°21.6′	79°00.2′	78°59.6′	23.7	56	0245	29.3	22/7	15	1.3
13	32°05.2′	32°06′	77°41.5′	77°39.5′	102	30	1830	28.9	24/7	12	2.1
14	32°19′	32°19.5′	77°33.5′	77°33.0′	92.8	30	0411	28.6	25/7	14	0.88
15	"	"	"	"	243.5	30	0411	28.6	25/7	16	7.6
16	"	"	"	"	1	30	0411	28.6	25/7	20	0.27
17	32°51.2′	32°53.8′	76°29.0′	76°27.4′	14.1	32	0045	29.4	27/7	18	1.0
18	"	"	"	"	95	32	0045	29.4	27/7	15	0.71
19	"	"	"	"	3	32	0045	29.4	27/7	19	0.27
20	32°54′	32°55.4′	76°24.0′	76°23.0′	29.5	30	0422	29.4	28/7	19	0.31
21	"	"	"	"	65	30	0422	29.4	28/7	19	0.75
22	33°36.0′	33°38.0′	76°13.5′	76°11′	19	60	0147	28.7	29/7	18	0.61
23	"	"	"	"	79.5	60	0147	28.7	29/7	17	0.80
24	35°12.6′	35°14.0′	74°00.5′	73°58.3′	38	60	1806	28.2	1/8	16	0.71
25	"	"	"	"	100	60	1806	28.2	1/8	6	0.46
26	35°35.0′	35°35.7′	74°12′	74°15.4′	21.8	60	2345	27.8	1/8	12	0.61
27	"	"	"	"	288	60	2345	27.8	1/8	17	6.4
28	35°33.4′	35°35.0′	74°00.0′	73°58.0′	81.8	60	0215	27.8	2/8	13	0.89
29	"	"	"	"	384	60	0215	27.8	2/8	15	2.8
30	37°07′	37°11′	70°20′	70°17′	70	60	0045	28.2	5/8	16	0.21
31	"	"	"	"	318	60	0045	28.2	5/8	12	1.1
32	37°22.0′	37°26.0′	70°13.0′	70°09′	187	60	0325	27.2	5/8	16	6.0
33	"	"	"	"	201	60	0325	27.2	5/8	17	1.9
34	37°05.0′	37°07.0′	69°44.5′	60°39′	37.4	60	1030	27.4	5/8	17	0.76
35	"	"	"	"	60	60	1030	27.4	5/8	18	1.7
36	37°43′	37°39.9′	62°23′	69°18.0′	378	60	0627	27.8	6/8	15	5.5
37	"	"	"	"	386	60	0627	27.8	6/8	15	2.3
38	37°41′	37°47′	69°17′	69°13′	547	60	0837	27.8	6/8	13	3.3
39	38°25′	38°24′	66°28′	66°26′	110	60	0220	24.8	8/8	16	3.9
40	"	"	"	"	48	60	0220	24.8	8/8	9	0.20
41	37°48′	37°51′	62°39′	62°37′	233	60	2015	27.5	11/8	16	2.0
42	"	"	"	"	466	60	2015	27.5	11/8	16	2.6

MATERIALS AND METHODS

There are two aspects of the experimental procedure for the determination of the summer abundance of zooplankton in the Gulf Stream. The first involves the collection program from the Lynch cruise, and the second involves the classification and population determinations in the laboratory.

Forty-two horizontal plankton hauls from the Lynch were made at 23 locations listed in Table I. Depths ranged from 1 to 547 meters and the durations were usually 60 minutes, with some shorter, at varying times of day and night (Table I); the surface water temperature was indicative of the Gulf Stream water at all stations on the dates shown. A number of hauls were made at nearly the same depths (Station 6, 8, 11, 12, and 26; 36 and 37; 32 and 33; 10 and 16) to check the consistency between tows.

Tows were made with a 12-inch (30.5 cm) mouth Clarke-Bumpus automatic plankton sampler with a 100 μm mesh (Kahl Scientific Instrument Corporation). The counter on the flow meter was later found to register improperly, and the flow was estimated based on published data. The Clarke-Bumpus towing assembly is unflared. Tranter and Heron (1967) give the filtration efficiency as 80% at a towing speed of 1 knot with a mesh width of 260 μm. Our towing speed was 1 knot for all samples and the mesh opening was 100 μm. Using Table 9 of Tranter and Heron (1967) and interpolating for a 100 μm mesh opening, the effect of this opening compared to a 260 μm mesh is an efficiency of 88%. The over-all efficiency is the product which is 70.4%. The net had a porosity of 36%. The volume of water passing through this net is reduced below that passing through the 30.5 cm diameter mouth of the sampler by the efficiency of the sampler and the porosity of the net. The volume of water passing through this net in 1 hour at a 1 knot towing speed is 34.2 cubic meters. Tranter, Kerr, and Heron (1968) indicate that a 1 knot hauling speed is reasonable.

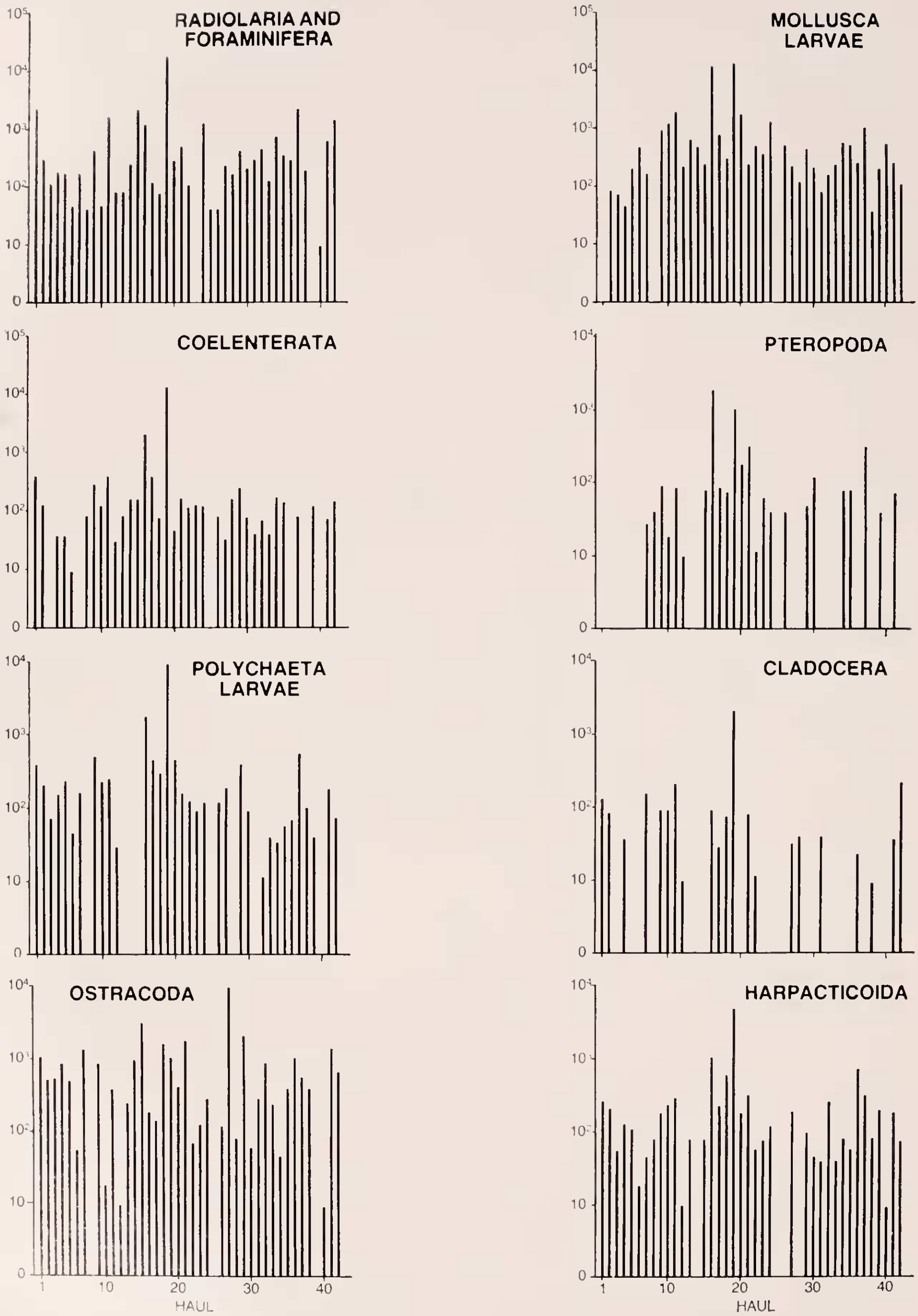
The jumbo Clarke-Bumpus sampler is of reasonable size for depths up to 500 meters, being comparable with the 80 cm diameter Juday nets used by Soviet expeditions for these depths (Vinogradov, 1970); their mesh size was 180 μm, and Riley (1939) for instance, used a 160 μm mesh. Our use of a 100 μm mesh net was intended to capture smaller as well as large zooplankton. The mesh was also fine enough to capture large phytoplankton and yet not clog with nannoplankton. The Gulf Stream nevertheless generally has a low phytoplankton population (see Egan, 1974, for instance). Tows were made at varying times of day.

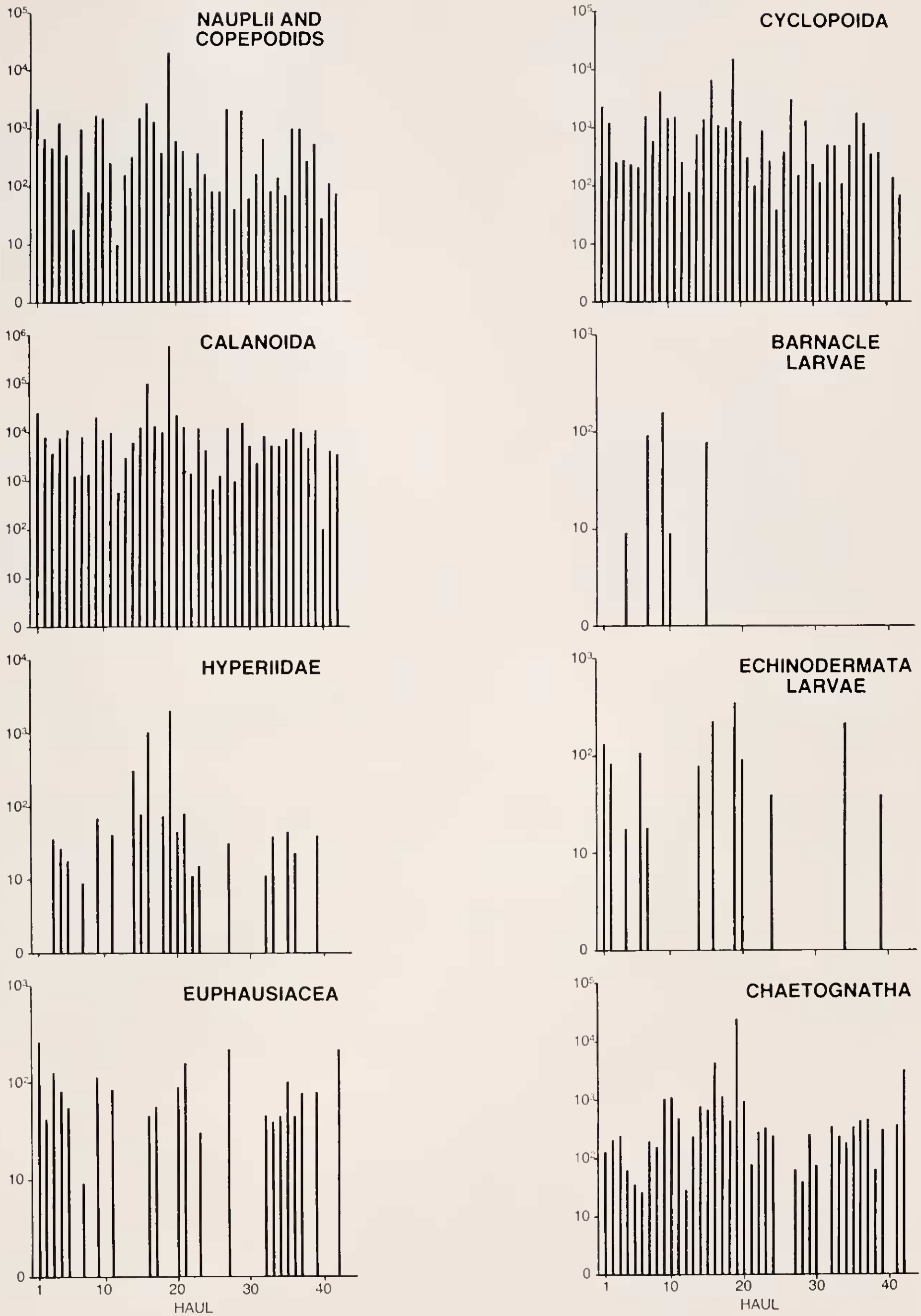
Concurrently with the plankton sampling, observations were made of sea conditions, surface winds, and cloud cover; the object of these observations was to infer the degree of sea surface mixing in the Ekman wind-drift layer (Stommel, 1958) and to determine the solar irradiance available for primary production.

Collected zooplankton were preserved with a formalin solution and stored in Mason jars. Separation of the zooplankton was accomplished by allowing the contents of the Mason jars to settle, which took four years because of the priority of validating our optical instrumentation (Egan and Cassin, 1973). A measured portion of the supernatent liquid in the jars was decanted (about half) because it contained little or no biota and the remainder was a concentrate of zooplankton. It was stirred to produce a homogeneous mixture. Between 4 and 10 four-milliliter aliquots were pipetted off this concentrated mixture and analyzed. The number of aliquots depended upon the density and diversity of the sample. The data was corrected to the original full sample volume.

Using a gridded counting disk, the total number of zooplankton in each aliquot was counted with a binocular stereo microscope at magnifications up to 70×. Additional identifications were made with a compound microscope at magnifications up to 1000×. Ratios between phytoplankton retained in the net and zooplankton were calculated. The number of phytoplankton was determined by counting large cells (*e.g., Ceratium*) and chains of smaller cells. Thus the ratio was not calculated as cells per zooplankter, but alternately as large cells and chains per zooplankter. Four replicates were counted for each sample.

In order to get an estimate of the zooplankton biomass, dry weight determinations were made. A correct determination would have required destruction of all our samples, which still could be useful for species determinations beyond that reported on in this paper. In order to conserve the major portion of our samples, we adopted an approximate approach. The method consisted of counting out


RADIOLARIA AND FORAMINIFERA
MOLLUSCA LARVAE
COELENTERATA
PTEROPODA
POLYCHAETA LARVAE
CLADOCERA
OSTRACODA
HARPACTICOIDA
0
10
10^2
10^3
10^4
10^5
1
10
20
30
40
HAUL


NAUPLII AND COPEPODIDS
CYCLOPOIDA
CALANOIDA
BARNACLE LARVAE
HYPERIIDAE
ECHINODERMATA LARVAE
EUPHAUSIACEA
CHAETOGNATHA
1
10
20
30
40
HAUL

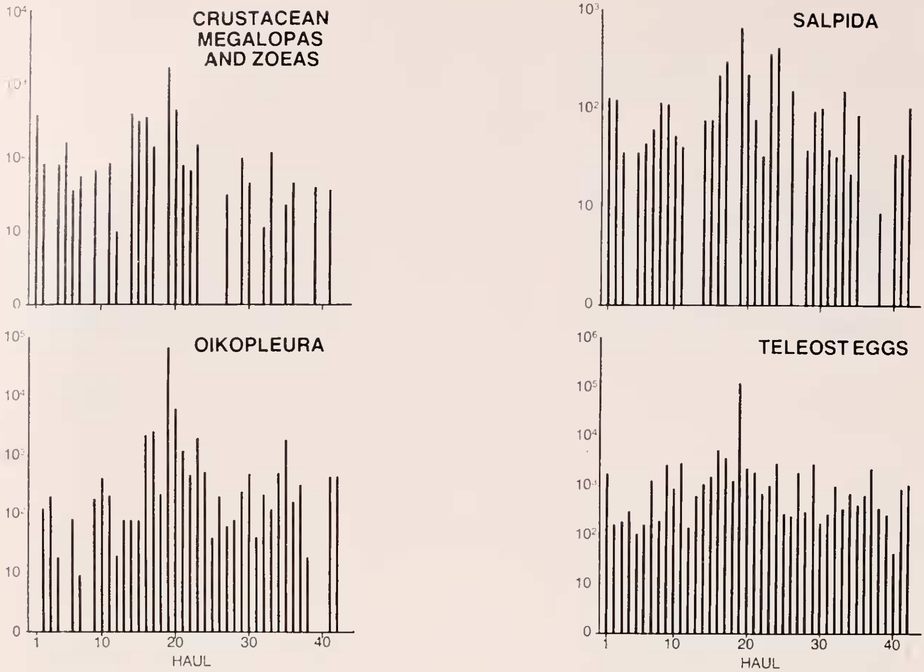


FIGURE 1. Comparison of zooplankton populations by taxa and haul. Vertical axes represent individuals per 100 m³, and the horizontal axis represents the 42 hauls in chronological order. (Data on file at National Oceanographic Data Center Accession Number 75–0732.)

the first 500 zooplankton individuals and filtering them on a tared millipore filter pad that had been previously heated for one hour at 100° C. The sample was then placed in a drying oven at 100° C for a period of 24 hours, after which time it was weighed on a Mettler H20 balance, and the weight recorded. Replicates from three random stations were made. Calculations could then be made of the average weight per zooplankton individual. This factor was then multiplied by the average number of individuals per m³ in order to arrive at the dry weight biomass determination.

Correlation coefficients were calculated relating total zooplankton and taxa to depth, local time of day, latitude, and longitude.

RESULTS

Laboratory analyses of the 42 hauls are presented in Figure 1. There are twenty taxa represented, and the populations per 100 m³ are plotted versus station (the numerical data is on file at the National Oceanographic Data Center, Accession Number 75–0732). A logarithmic ordinate is used because of the large range of population variation between stations. A zero ordinate indicates absence of the taxon at the station. Additionally, Table I lists, by haul, the number of

TABLE II

Correlation matrix for total zooplankton with depth, location, and local time, and comparison with Gulf Stream chlorophyll data.

	Depth	Latitude	Longitude	Time
All zooplankton (Time: 0 to 1200 hr)	0.035	0.298	−0.267	−0.533
All zooplankton (Time: 1200 to 2400 hr)	−0.186	−0.102	0.090	0.054
Zooplankton at depths <100m	−0.329	−0.105	0.077	0.106
Zooplankton at depths between 100 and 300m	0.660	−0.552	0.555	−0.137
Zooplankton at depths >300m	0.007	0.221	−0.092	−0.055
Chlorophyll-*a* and chlorophyll degradation products	0.054*	0.211*	−0.317*	—

* Calculated from data of Egan, 1974.

major taxa present and the ratio of zooplankton to phytoplankton. Table II presents the correlation matrix for total zooplankton with depth, location (in terms of latitude and longitude), and local time, with a comparison to cholorphyll data. Table III lists the average population per 100 m^3 over all 23 stations and the depth and latitude correlations.

Referring to the taxa shown in Figure 1, and Table I (the next to the last column where the number of taxa present are listed as a function of depth), the correlation (ranges from +1 through 0 to −1, where 0 is no correlation) between

TABLE III

Average population per 100m^3 over all 42 hauls, and correlation coefficients for depths and latitude.

Taxa	Population	Depth Correlation	Latitude Correlation
Radiolaria and Foraminifera	833	−0.10	−0.07
Coelenterata	443	−0.19	−0.09
Polychaeta larvae	402	−0.18	−0.10
Mollusca larvae	1,000	−0.29	−0.12
Pteropoda	114	−0.24	−0.09
Cladocera	84	−0.14	−0.11
Ostracoda	794	0.29	0.02
Nauplii and Copepodids	1,079	−0.11	−0.13
Calanoida	23,590	−0.18	−0.09
Harpacticoida	275	−0.15	−0.07
Cyclopoida	1,321	−0.14	−0.18
Barnacle larvae	8	0.10	−0.25
Hyperidae	98	−0.23	−0.12
Euphausiacea	48	0.32	−0.10
Crustacean megalopas and zoeas	121	−0.20	−0.22
Echinodermata larvae	33	−0.27	−0.18
Chaetognatha	1,040	−0.16	−0.07
Salpida	100	−0.32	−0.11
Oikopleura	2,106	−0.19	−0.07
Teleost eggs	4,174	−0.17	−0.07
Miscellaneous	51	−0.10	0.05
Total	37,714	−0.18	−0.09

taxa and depth is small (calculated to be +0.037). Some regions of the ocean have a very strong dependence of species on depth (Vinogradov, 1970). However, there is a stronger correlation of the ratio of zooplankton to phytoplankton (last column, Table I) with depth (calculated to be +0.357).

If we consider the total zooplantkton population, and calculate the correlation matrix for depth, location, and local time, we obtain Table II. The matrix breaks up the time analysis into two intervals 0 to 1200 hr and 1200 to 1800 hr to check migration. The time is taken as the average time of the haul and corrected for local time at the tow site. There is a significant correlation with time between 0 and 1200 hr indicating a depletion of the zooplankton in the sampling depth range. Also a latitude-longitude dependence appears, the latitude effect being the opposite of longitude (resulting from the course of the cruise); the strongest effect is an increase in total zooplankton between 0 and 1200 hr with increasing latitude.

If we consider depth effects (Table II) and use three depth intervals (< 100m, 100 to 300m, and > 300m), we see that the total zooplankton decrease with depth for < 100m, increase with depth between 100 and 300m, and have negligible dependence at > 300m. The latitude dependence shows a depletion of the region < 300m depth with progress northward and an increase at depths > 300m.

A comparison with data derived from Egan (1974) indicates an increase in chlorophyll-*a* and chlorophyll degradation products with northward progress of the Gulf Stream. In comparison, the calculated correlation of the total zooplankton with latitude is negligible (−0.090).

Referring to Figure 1 and Table III, and based on more detailed correlation analyses by us, there is no unique correlation of the 20 taxa with depth, location, or time of day. Only latitude is given because of its approximately inverse relation to longitude for this cruise. The miscellaneous classification included such minor zooplankton as enteropneust larvae, teleosts, isopods, sponge amphiblastula, nematodes, *Ergasilus,* and phoronid actinotrocha. Also, all hauls included phytoplankton that did not pass through the 100 μm mesh plankton net; typical were *Ceratium, Chaetoceros, Asterionella,* pennate diatoms, and long unidentified chains. The numerical ratio of zooplankton to phytoplankton varied from 0.13 to 10.7, averaging 2.33 (Table I); however, this ratio is only a qualitative indication of the presence of phytoplankton because many long chains were observed, each counted as one, even though consisting of many cells. Also nannoplankton that passed through the net mesh would cause an additional phytoplankton volume that is not enumerated.

Three surface tows were made (Hauls 10, 16, and 19, Table I). Two show extraordinarily high populations, particularly calanoids (Hauls 16 and 19). These latter two hauls were off the coast of Georgia where unusually large standing crops may occur (Hart, 1942). These hauls evidenced large phytoplankton content also.

Even though Haul 38 was taken at a depth of 547 meters (Table I), there was a calanoid population of 2600 per 100 m^3 (Figure 1). Comparing this to the average over 42 hauls (Table III and Figure 1), it can be seen that the calanoid population may vary greatly from haul to haul with appreciable population at greater depths. Figure 1 also depicts that the ratio among the taxa between hauls may vary considerably.

Another interesting observation exists for Hauls 36 and 37; both were made at the same time, at almost the same depths (378 and 386m, Table I). The calanoid population for Hauls 36 and 37 was 11600 and 9860 per 100m³ (Figure 1 and Table I), and the number of major taxa present was the same (15).

There are other comparisons that may be made among the data that show that the zooplankton population distribution and concentration varied considerably during July and August, 1969, in the Gulf Stream. However, as noted previously, there does not appear to be any consistent buildup in any of the zooplankton population taxa with northerly drift in the Gulf Stream. Nor does there appear to be any systematic decrease.

Discussion

The most significant result of this study is that there is no significant over-all population increase or decrease of zooplankton with progress north in the Gulf Stream under the summer conditions that existed in 1969. Also, there is no significant consistent correlation of total zooplankton with depth, time of day, or location.

In order to explain these seeming inconsistencies, we must consider the hydrology of the Gulf Stream, and concur in the hypothesis that there must be a considerable influx of zooplankton-laden continental shelf water (Warren and Volkmann, 1968). This influx of continental shelf water mixing with the Gulf Stream would be expected to cause considerable variations in the zooplankton (and phytoplankton, as well as nutrients) and result in the observed biological data.

It has already been noted that the volume transport of the Gulf Stream increases with northward progress. Preliminary analyses indicate that the mechanism of momentum transfer from the Gulf Stream is by means of a geostrophically-balanced inflow (Sturges, 1968); the deep water shear is about 1 cm/sec in 3 km. This geostrophically balanced inflow is not a meander that may grow into a detached eddy (Hansen, 1970). Surface mixing to the depth of the Ekman Layer (about 50m) can occur by means of shear from surface winds (Stommel, 1958).

The present concept of Gulf Stream transport deduced from the observations of Warren and Volkmann (1968) (between 37 to 38° N and 67 to 71° W) implies a considerable inflow of slope water. There is also a southward flow of Labrador Sea water (which could contain zooplankton) at depths between 1000 to 3000m underneath and into the Gulf Stream. The relative inflow amounts are conjectured to be 5×10^6 m³/sec on the inshore side of the Gulf Stream and 30 or 40×10^6 m³/sec on the offshore side (W. Sturges, Florida State University, Talahassee, private communication, 1974). It is conceded that a noncontroversial hydrological model of the Gulf Stream does not exist. There is no consistent trend of zooplankton population along the surface ship cruise that moved with the velocity of the Gulf Stream (*i.e.,* approximately 1.6 knots: Naval Oceanographic Office, 1965). A decrease in zooplankton population or increase should show some trend with drift northward in the Gulf Stream.

One might conjecture that the forementioned influx of Labrador Sea water would carry with it a representative boreal zooplankton population and nutrients. Boreal species are fewer than warmer water types (Sverdrup, Johnson, and

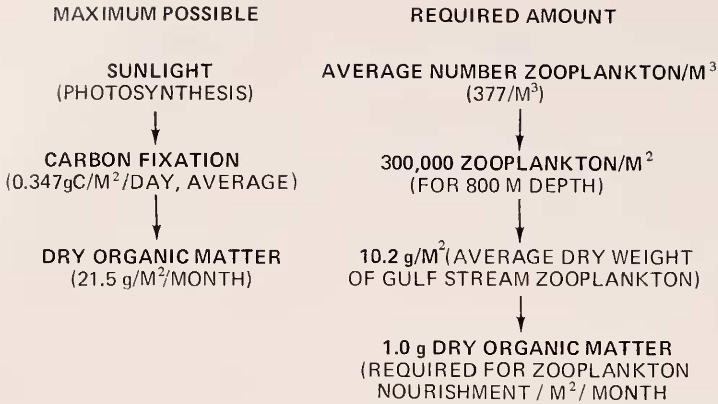


FIGURE 2. Gulf Stream ecology (zooplankton nourishment).

Fleming, 1942), but identification to the species level was not included in our observations. These determinations could be accomplished subsequently but are not essential to this paper.

As mentioned in the introduction, Clarke (1940) and Grice and Hart (1962) have studied the abundance of zooplankton along transects south of the Grand Banks. Also, Bowman (1971) has studied the distribution of calanoid copepods off the southeastern United States between Cape Hatteras and southern Florida. Clarke (1940) determined zooplankton abundance by means of a volume measurement and found (in agreement with us) that the amounts of plankton caught were extremely variable, even at neighboring stations.

Grice and Hart (1962) found in three collections that the zooplankter abundance in the Gulf Stream ranged between 99 and 156/m^3, which is less than our average of 377/m^3 (Table III).

Bowman (1971) quantitatively determined individual species of calanoids, and it is possible to extend our work by doing this; but we primarily sought to determine general classifications in order to analyze the ecology of the Gulf Stream and the additional detail was unnecessary.

The characterization of the Gulf Stream ecology is outlined in Figure 2. A comparison is made between the calculated dry organic matter available and the food requirements of zooplankton in the Gulf Stream. These calculations are based on the measurements described in this paper with that deduced from published experimental and theoretical relationships.

In detail, Table III indicates that there are on the average 377 individuals/m^3 for the cruise considered. The depth of the Gulf Stream is assumed to be approximately 800m (Naval Oceanographic Office, 1965). We have determined that the average dry weight of a Gulf Stream zooplankter is 0.034 mg, and in June about 10% of the dry zooplankton weight is required to support it for a month (Riley and Bumpus, 1946, based on Georges Bank data). Then 1.0 g/m^2 per month of phytoplankton would be required to nourish the zooplankton (Figure 2).

We compared this calculated requirement with that possible based on photosynthesis and measured cholorophyll concentrations in the Gulf Stream. Because the photosynthetic rate depends upon the incident solar irradiance, bi-hourly observations were made of cloud cover (C_0) during the cruise and this permitted average daily solar radiation (Q) totals to be calculated from Kimball, 1928; *i.e.*, $Q = Q_0\ (0.29 + 0.7\ [1.0 - C_0])$. The value of Q_0 was taken as 432 for July and 399 for August in gram cal/cm². The amount of carbon fixed per day was calculated from the expression $p = R/k \times C \times 3.7$ (Ryther, 1956). An average was then calculated over the cruise duration.

For clear (Gulf Stream) water, the extinction coefficient is $k = 0.02$. The factor R depends upon Q, and is determined from a graphical relation between solar radiation and relative photosynthesis rate (Ryther and Yentsch, 1957). The quantity C in grams of cholorophyll per cubic meter in the water column is based on *in situ* Gulf Stream measurements of cholorophyll (Egan, 1974) made concurrently with the net tows. Riley (1939) has made measurements of the vertical distribution of plant pigments in the Gulf Stream; the concentration approaches zero at a depth of 400m, with the average approximately given by the numerical value at 200m depth. [Even though Riley, 1939, used Harvey plant pigment units (HPPU) in the paper, there is a conversion relationship to chlorophyll given by Strickland, 1960: mg chlorophyll = $(3 \pm 1) \times 10^{-4}$ Number of HPPU. This value agrees with that calculated from (Riley, 1939) surface measurements within a factor of 2.09]. Riley (1939) thus indicated that the average level in the Gulf Stream would be about (0.3 ± 0.1) mg/m³ of chlorophyll. The chlorophyll-*a* and cholorophyll degradation product measurements of Egan (1974) were made at depths from 120 to 569m, at an average depth of 253m. Using this data (average 0.14 mg/m³ chlorophyll-*a* and chlorophyll degradation products) as representative of the average level of cholorophyll per cubic meter in the water column, we may then compute the quantity of carbon fixed per day, taking into account cloud cover. The average quantity of carbon fixed was calculated to be 0.347 g/m²/day. The corresponding dry organic matter (17 μg carbon $\equiv$ 35 μg dry organic matter: Cushing, 1958) was 21.5 g/m²/month (30 days). This is at least ten times that required to sustain the zooplankton population throughout the Gulf Stream (Figure 2) and would lead to a phytoplankton excess. This does not occur (Riley, 1939). It is rather improbable that there is a nutrient limitation because the nitrate to phosphate ratio was found to be 15:1 for the southern stations (Riley, 1939); Ryther and Dunston (1971) have shown that the inorganic nitrogen often appears to be the limiting factor in algae production in coastal waters. The southern station value of 15:1 is considerably higher than their value of 6:1. Various mineral sources, and transport of these minerals, have been reported that can supply the Florida Current, and subsequently the Gulf Stream (Jacobs and Ewing, 1969). It is possible that there is a micronutrient deficiency (such as iron, manganese, or vitamin B_{12}) which could limit the phytoplankton population (Raymont, 1963).

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Summary

We have described the results of laboratory analyses of 42 horizontal tows using a Clarke-Bumpus plankton sampler with a 100 μm mesh net in the Gulf Stream. Classifications of 20 zooplankton taxa have been made for the 42 hauls. Calanoids dominate the hauls. It was found that the zooplankton population distribution and density varied considerably from haul to haul, but there was no consistent buildup or depletion of population with progress of the flow north in the Gulf Stream. These biological arguments reinforce previous conjectures that there is a geostrophically-balanced inflow of continental shelf and Labrador Sea water that gradually mixes with the Gulf Stream water mass. These inflows provide sources of zooplankton and phytoplankton to the Gulf Stream as it progresses northward. Also, an ecological analysis of the Gulf Stream indicates that the dry organic matter is over an order of magnitude below that which is theoretically possible.

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